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Weld Formation in Microgravity

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In order to investigate the effect of gravity on the formation of a weld, gas tungsten arc (GTA) welding was performed both in a microgravity environment and in a terrestrial environment. The microgravity environment was produced for 10 sec with less than 10^{-5} G by a drop-shaft type microgravity system at Japan Microgravity Center (JAMIC). The material used was an aluminum alloy. It has become clear that in the microgravity environment, the weld bead is formed flatly and a large amount of metal can be welded at once and in any welding position though the weld shape is significantly affected by gravity in the terrestrial environment. When helium rather than argon is used as a shielding gas, the butt weld is formed more flatly because the arc pressure is reduced. Judging from the distribution of the grain structures in the weld, in the microgravity environment, the temperature gradient is smaller than that in the terrestrial environment, and the degree of the constitutional supercooling is higher due to the absence of the heat transfer by gravity.

KEY WORDS: microgravity environment; shielding gas; gas tungsten arc welding; weld bead; bead-on-plate weld; butt weld.

1. Introduction

Welded joints are more airtight and reliable than those prepared with any other methods. Such characteristics are indispensable for constructing space structures. In order to use currently available materials in space for a long period, welding processes are essential because the repair of structures and the assembly of parts are required in space. The first welding experiment in space was performed in 1969, by the USSR during the "Vulkan" experiments of the Soyuz-6 mission.[1)] The first US experiment on space welding was conducted in 1973, aboard the Skylab.[2)] However, the detailed information on the welding phenomena in space is not very open to the public. In Japan, welding experiments have not yet been carried out in space and even welding in a microgravity condition is scarcely reported in spite of its importance.[3–5)] In order to estimate the strength of joints welded in space, it is necessary to clarify the effect of gravity on the formation of welds.

In this study, gas tungsten arc (GTA) welding was carried out using a drop-shaft type microgravity system at Japan Microgravity Center (JAMIC). The system can produce 10 sec microgravity with a high quality microgravity condition. The difference in weld formation between in the microgravity environment and in a terrestrial environment is investigated.

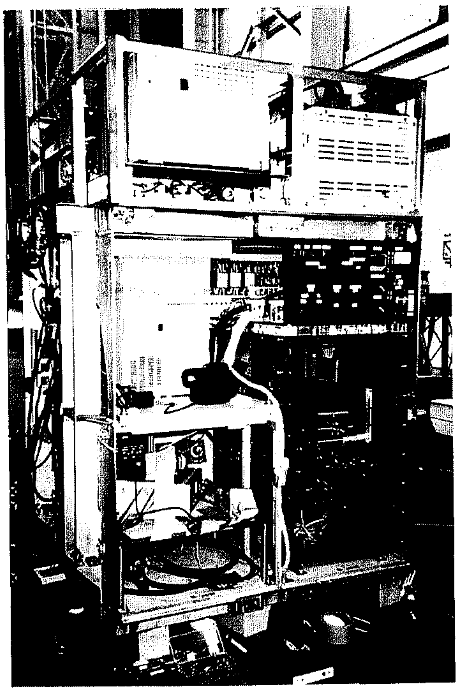
2. Space Environment

The environment in space is different from that on earth in several respects. The first is the degree of gravity. In space, typical gravitational acceleration is between 10^{-4} and 10^{-6} G, and therefore the effects of buoyancy, sedimentation, and hydrostatic pressure are negligible. The second is that space is in a vacuum condition. For example, typical levels in the low earth orbit (LEO) are between 10^{-4} and 10^{-8} Pa.[6)] The third difference is in the degree of temperature variation. It has been reported that the temperature of a space structure varied from −90 to 200°C.[7)] The fourth difference is an atmospheric composition. Atomic oxygen formed by the photo-dissociation of molecular oxygen is the most prevalent species in the LEO[8)] and is one of the most severe threats to space structures. In the LEO, space debris and micrometeroids are also traveling at very high speeds, about 8 km/sec, and therefore, they sometimes damage or destroy space structures.

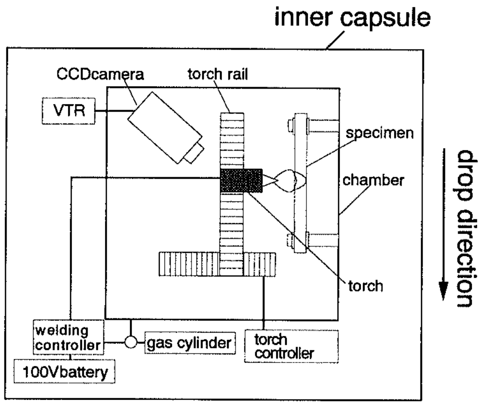
3. Experimental Apparatus and Procedure

3.1. Experimental Apparatus

Microgravity environments can be achieved by several methods. The first method is to carry out experiments in space,[1,2)] the second is to fall an aircraft[3)] or a rocket with a flying laboratory, and the third method is to fall a drop capsule through a drop-shaft.[4,5)] The first method costs too much. Although the second method provides longer duration, the quality of microgravity is lower than the drop-shaft type. In this study, we used the drop-shaft type microgravity facility at JAMIC. The system can maintain 10 sec microgravity with a microgravity con-



(a) Experimental apparatus



(b) Schematic of apparatus

Fig. 1. GTA experimental apparatus.

Table 1. Chemical composition of the aluminum alloy. (mass%)

Al	Mg	Mn	Fe	Cr	Si	Cu	Zn	Ti
Bal	4.41	0.62	0.21	0.12	0.09	0.02	0.02	0.02

dition of less than 10^{-5}G. The quality of microgravity of the system is the highest up to the present[9] and is similar to the space environment. The drop capsule is composed of a double structure consisting of an inner and an outer capsule and a vacuum is maintained between them so that the free fall velocity of the inner capsule will not be affected by the air drag. A small-sized GTA welding apparatus is accommodated in the inner capsule. The size of the apparatus is $0.87\,\mathrm{m}^{w} \times 0.87\,\mathrm{m}^{l} \times 0.92\,\mathrm{m}^{h}$. **Figure 1** shows the GTA welding apparatus used in this study. The apparatus consists of a welding chamber, a battery, a welding power source, a shielding gas supply and a welding control system. The welding chamber is equipped with a specimen, a torch sliding system and a CCD camera to observe the weld pool. The battery is an uninterruptible power system (UPS) which supplies 2.4 kW (AC100V, 3000VA) to the welding power source. The welding power source is a constant current type.

3.2. Materials and Welding Conditions

The material used was an aluminum alloy. It was selected as a material commonly used in aerospace. **Table 1** shows the chemical composition of the aluminum alloy. Pure silver (99.99 mass%) was also used to investigate the effect of oxide film on welds. **Table 2** shows the welding conditions. Bead-on-plate welding as well as butt welding was performed. The welding positions were vertical up and horizontal. The polarity was the direct current electrode negative (DCEN). Note that, in this study, the electric power rather than the welding current was set to be the same for the different two shielding gases. The shielding gas flow rate was optimized in a terrestrial environment and all specimens were welded with the same GTA welding apparatus. Some of them were welded in the microgravity environment and the others in the terrestrial environment.

In order to investigate the weld shape and the microstructure, the welds were observed using a polarization microscope after cutting, mechanical polishing and electrical etching the specimens.

4. Results and Discussion

4.1. Effect of Gravity on Weld

Figures 2 and **3** show transverse sections of the bead-on-plate welds and the butt welds formed in horizontal welding with argon shielding gas in both environments, respectively. As shown in Figs. 2(a) and 3(a), in a terrestrial environment, the weld bead is hollowed out in the upper part and is bulged very much in the lower part. In this case, the molten metal drops in the gravity direction and is solidified there. In a microgravity environment, on the other hand, the weld pool is maintained and the weld bead is formed more flatly due to the lack of gravity, as shown in Figs. 2(b) and 3(b).

When argon is used as a shielding gas, the difference in the weld shape between in the terrestrial environment and in the microgravity environment is larger in butt welding than in bead-on-plate welding. This phenomenon indicated that the weld shape is affected by the arc

Table 2. Welding conditions.

	Aluminum alloy					Pure silver
Welding method	Bead-on-plate welding			Butt welding		Bead-on-plate welding
Sample size, $mm^l \times mm^w \times mm^t$	$160 \times 50 \times 3$			$160 \times 25 \times 3$ (a piece)		$160 \times 25 \times 3$
Shielding gas	Argon	Argon	Helium	Argon	Helium	Argon
Welding position	Vertical up	Horizontal	Horizontal	Horizontal	Horizontal	Vertical up
Welding current, A	80	80	52	80	52	80
Welding voltage, V	12	12	18	12	18	12
Welding velocity, m/sec	4.0×10^{-3}	3.6×10^{-3}	4.8×10^{-3}	3.6×10^{-3}	4.8×10^{-3}	2.9×10^{-3}
Shielding gas flow rate, m^3/s	8.3×10^{-5}	8.3×10^{-5}	1.7×10^{-4}	8.3×10^{-5}	1.7×10^{-4}	8.3×10^{-5}

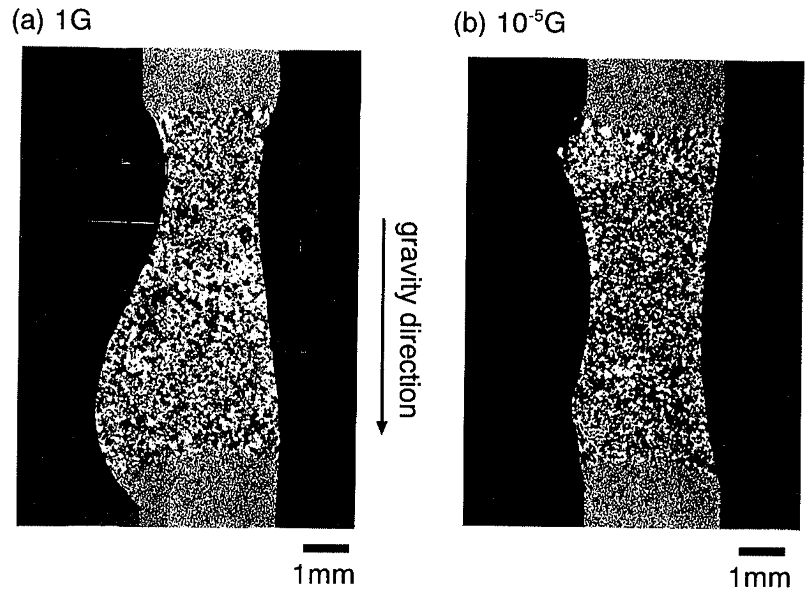


Fig. 2. Transverse sections of bead-on-plate welds in horizontal welding with argon shielding gas.

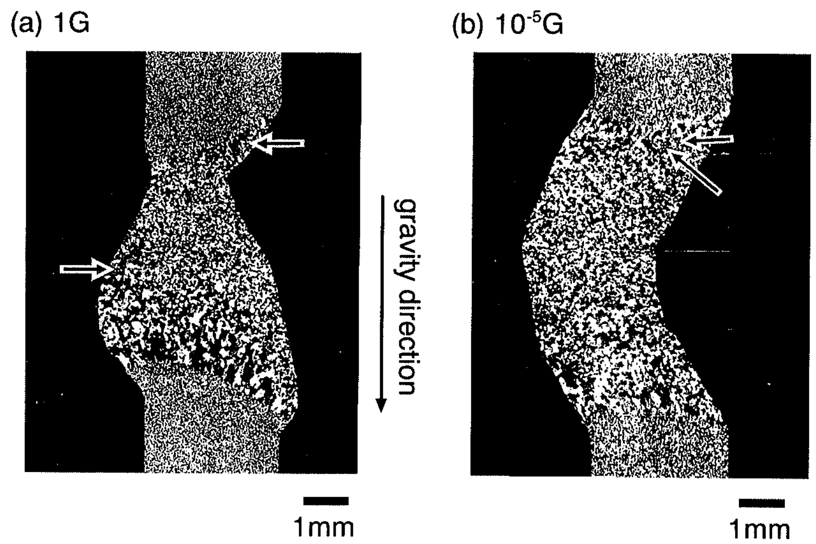


Fig. 3. Transverse sections of butt welds in horizontal welding with argon shielding gas. The arrows indicate the pores.

pressure more easily in butt welding.

In the terrestrial environment, the butt weld is smaller than the bead-on-plate weld. This result indicated that a small gap between the plates in the butt welding can cause a significant difference in the heat transfer. The gap also causes pores, as shown with arrows in Fig. 3 (and see Fig. 5). In particular, in a microgravity environment, more pores are left in the weld than in the terrestrial environment because the bubbles cannot be easily released from the weld pool before the solidifica-

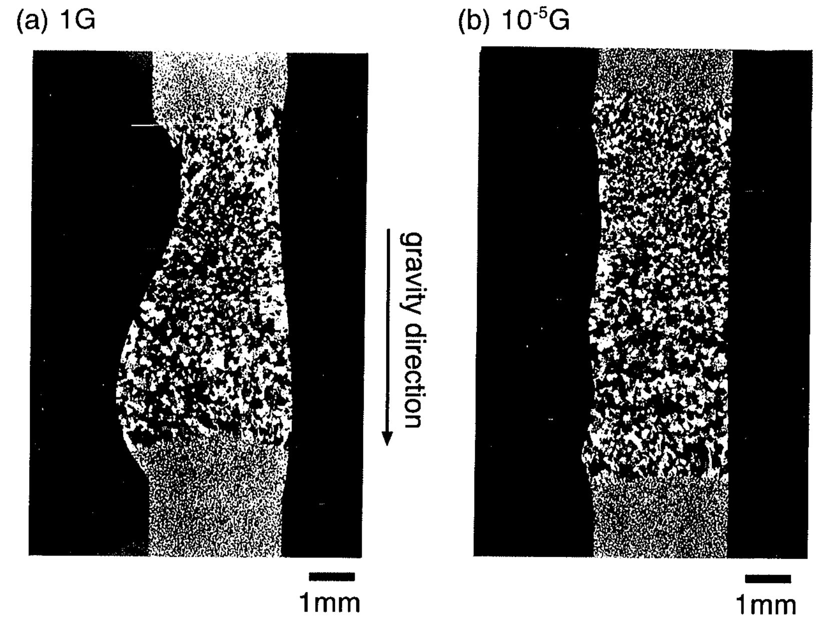


Fig. 4. Transverse sections of bead-on-plate welds in horizontal welding with helium shielding gas.

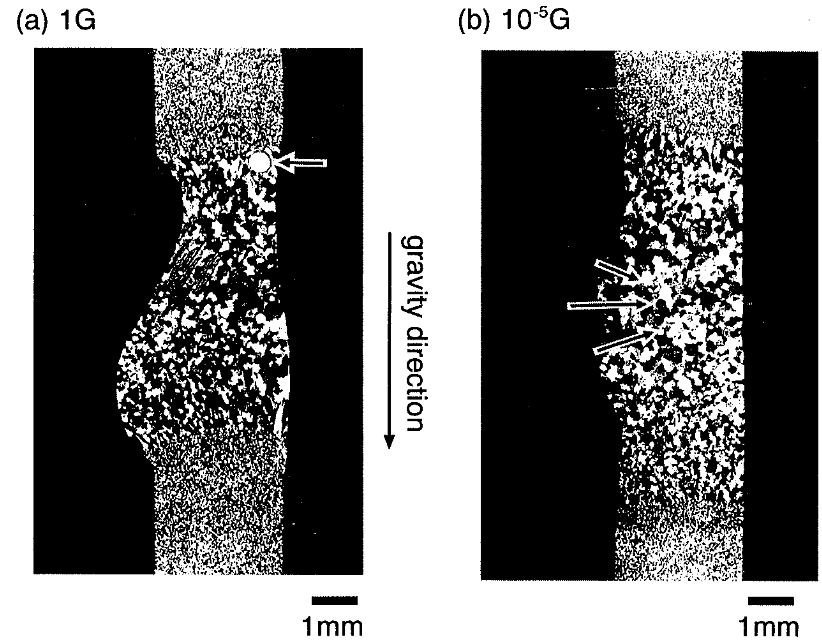


Fig. 5. Transverse sections of butt welds in horizontal welding with helium shielding gas. The arrows indicate the pores.

tion due to the lack of the buoyancy.

4.2. Effect of Arc Pressure

In order to investigate the effect of arc pressure, helium gas was used as a shielding gas. Hiraoka *et al.* reported that the arc pressure with helium shielding gas is about one third of that with argon shielding gas, under a condition of welding current; 200 A, arc distance; 5×10^{-3} m, shielding gas flow rate; $3.4\times10^{-4}\,m^3 s^{-1}$, and vertex angle of electrode; 30°.[10)]

Figures 4 and **5** show transverse sections of the bead-on-plate welds and the butt welds formed in horizontal welding with helium shielding gas in both environments, respectively. When helium is used as a shielding gas, both the butt weld and the bead-on-plate weld are formed flatter than those with argon shielding gas, as shown in Figs. 4 and 5. In particular, the welds formed in the microgravity environment are almost flat in both sides of the bead. Accordingly, it can be concluded that the maintaining force of the weld shape (*e.g.* the surface tension) is larger than the force by the arc pressure with the helium shielding gas. As mentioned before, an argon shielding gas is expected to produce several times larger arc pressure than a helium shielding gas. As a matter of fact the pressure bent the weld significantly in the butt welding, as shown in Fig. 3(b). However, the bead-on-plate weld was not bent even with the argon shielding gas. Accordingly, the force by the arc pressure with the argon shielding gas in this case seems to have been slightly larger than the maintaining force of

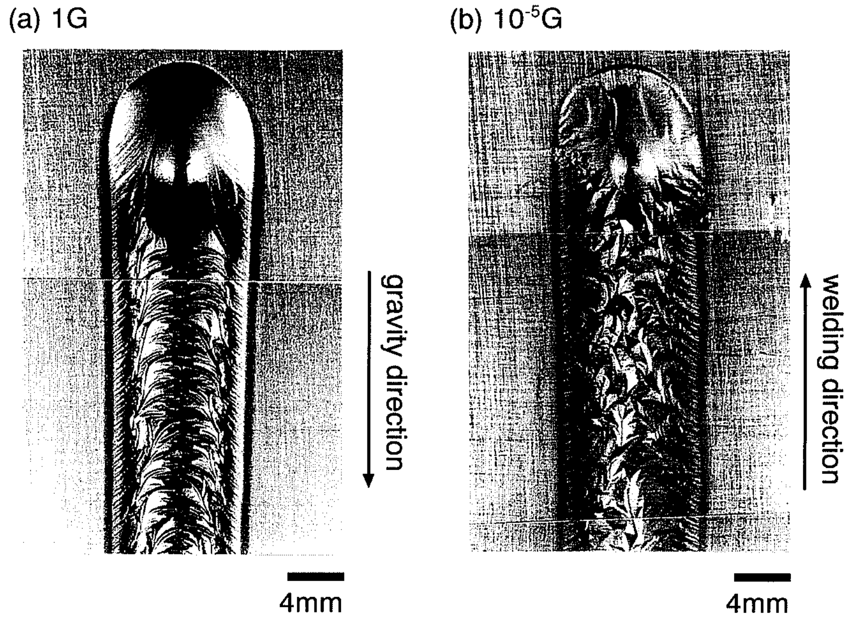


Fig. 6. Weld bead appearances of Al alloy in vertical up welding with argon shielding gas.

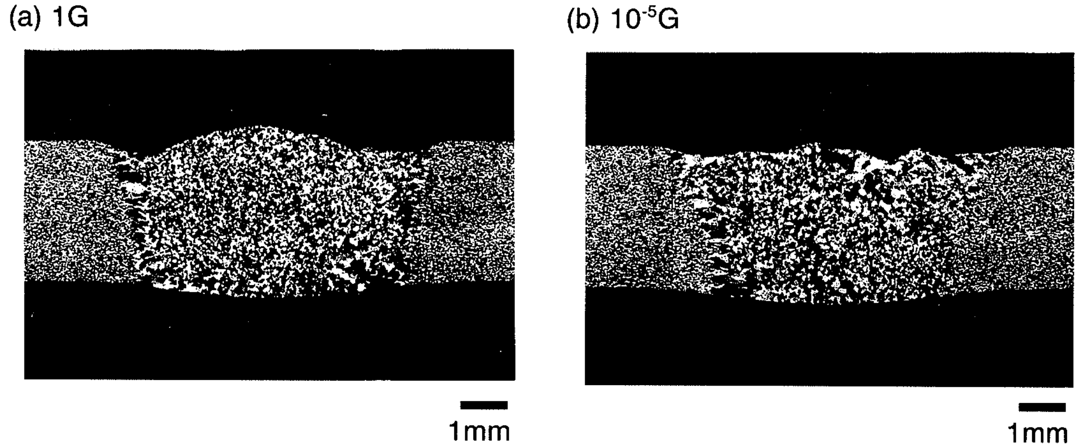


Fig. 7. Transverse sections of bead-on-plate welds in vertical up welding with argon shielding gas.

the weld shape.

It is considered that, even in the terrestrial environment, the maintaining force of the weld shape should be close to the force by the arc pressure with the argon shielding gas. However, because gravity forces the weld pool to drop and makes the effect of arc pressure unclear, it has been impossible to make a similar evaluation in the terrestrial environment.

4.3. Effect of Welding Position

In order to investigate the effect of welding position, welding was also performed in the vertical up position in both environments. **Figure 6** shows appearances of bead-on-plate welds of the aluminum alloy in both environments and **Fig. 7** shows transverse sections of the welds. As shown in Fig. 6, the irregular wrinkles are continuously observed on the surface of the weld in the microgravity environment though the ripples are observed on the surface of the weld in the terrestrial environment. These results indicated that the molten metal flows irregularly in the microgravity environment. In the microgravity environment, the weld bead is nearly flat as in the horizontal position. Thus, it is possible to weld in any welding position in a microgravity environment. In the terrestrial environment, on the other hand, the center of the weld bead is bulged. However, the difference in the weld bead is much smaller than expected. This is probably because the flow of the molten metal is restrained by the oxide films, as shown in Fig. 6.

In order to investigate the effect of oxide films on welding phenomena, pure silver is selected as a model material. **Figure 8** shows weld beads of the silver in both environments. As shown in Fig. 8(a), in the terrestrial environment, the weld pool fell away and a hole was formed by the effect of gravity. The paper behind the material can be seen through the hole. In the microgravity environment, on the other hand, the weld pool maintains its position on the specimen plate, even without the oxide films, and both the weld bead and the crater are flatter than those of aluminum alloy. This indicates a big advantage of the microgravity environment; welding can be performed with a large energy density forming a large weld pool in a microgravity environment.

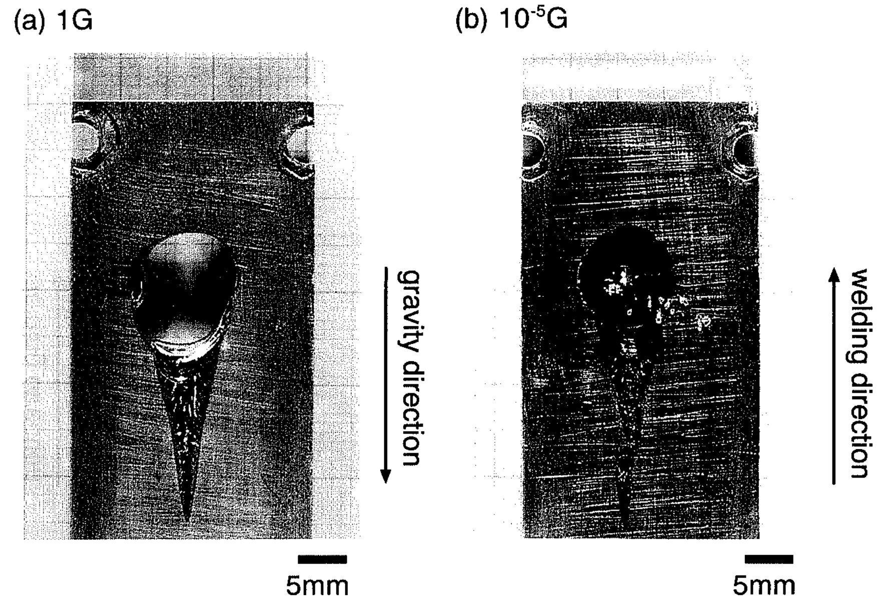


Fig. 8. Weld bead appearances of pure silver in vertical up welding with argon shielding gas.

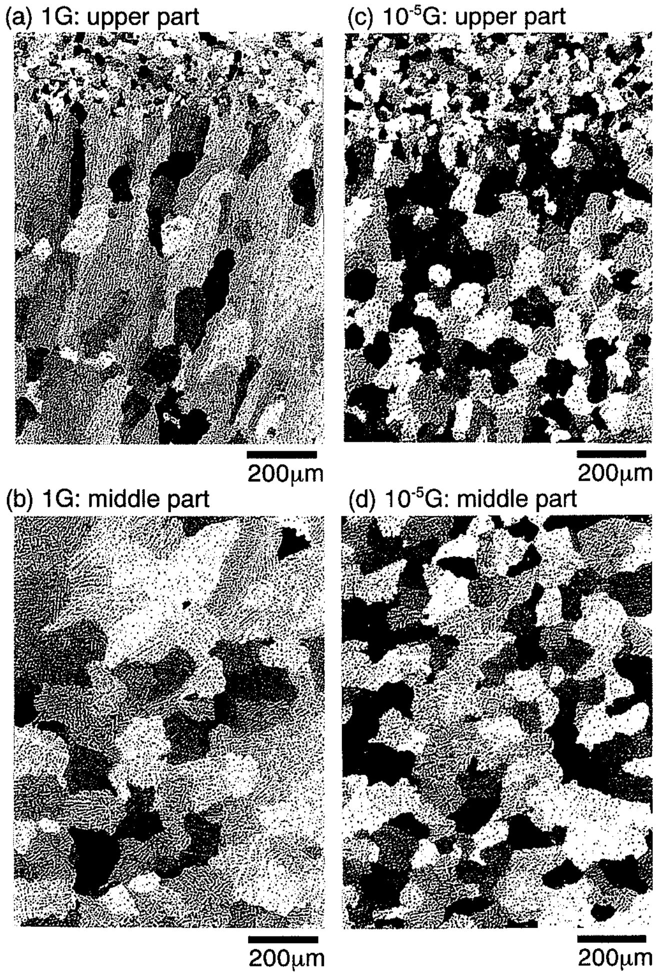


Fig. 9. Longitudinal sections of bead-on-plate welds formed in horizontal welding with helium shielding gas in both environments.

4.4. Microstructure and Solidification

Figure 9 shows longitudinal sections of the bead-on-plate welds formed in horizontal welding with helium shielding gas in both environments. In the terrestrial environment, the columnar grain structures are observed in the upper part of the weld and the equiaxed grain structures are observed in the other part, as shown in Figs. 9(a) and 9(b) (and see Fig. 4(a)). This result indicates that in the upper part of the weld the temperature gradient is larger and that the degree of the constitutional supercooling is lower. It is considered that the difference in the temperature gradient is caused by the heat transfer from the lower part to the upper part because of the molten metal drop in the gravity direction and that the upper part is cooled more quickly. In the microgravity environment, on the other hand, the equiaxed grain structures are distributed widely throughout the weld, as shown in Figs. 9(c) and 9(d). The temperature gradient should not be very different due to the absence of the molten metal drop.

Figure 10 shows the microstructure in the middle part of the welds in the microgravity environment. As shown in Fig. 10, when helium is used as a shielding gas, the size of the equiaxed grains is larger than those when argon is used. Thus, the cooling rate with helium shielding gas is smaller than that with argon shielding gas.[11] According to Senda *et al.*,[12] the cooling rate is in inverse proportion to a square of heat input. Accordingly, it is evident that the thermal efficiency with helium shielding gas is higher than that with argon shielding gas.

As shown in Figs. 3(b) and 5(b), in the microgravity environment, the columnar grain structures in the butt weld are observed more widely in both sides than those in the bead-on-plate weld. This result indicates that a larger temperature gradient in the butt weld is caused by the gap between the plates. The quantity of the weld pool in the butt welding of the terrestrial environment (Figs. 3(a) and 5(a)) is smaller than the others. This result indicates that the gap between the plates affects the heat transfer in a terrestrial environment, but that the gap does not affect the heat transfer very much in a microgravity environment.

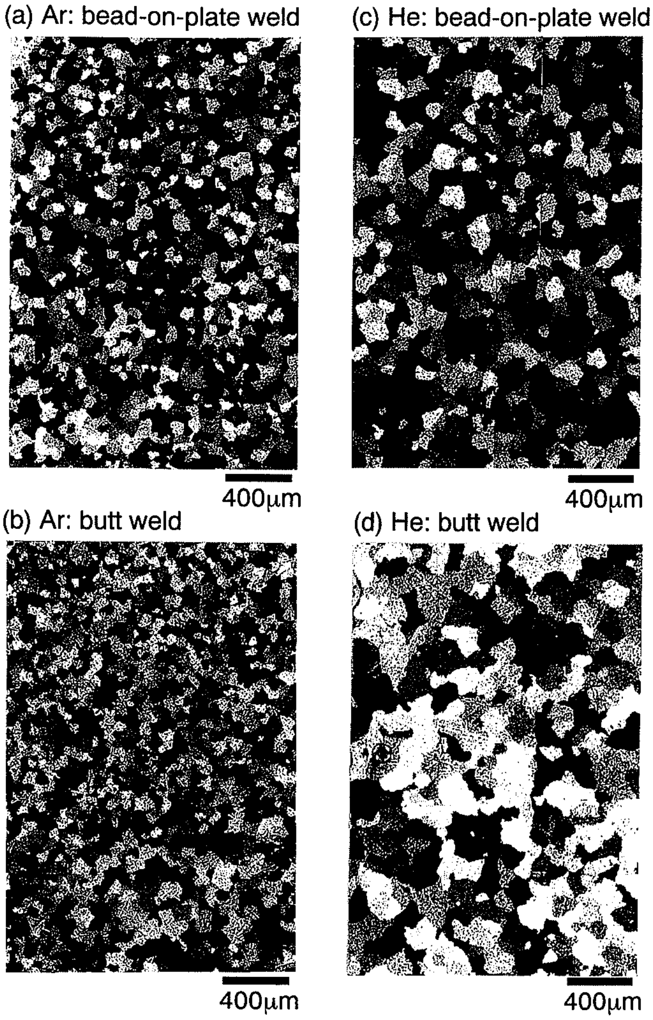


Fig. 10. Difference in grain size between with argon shielding gas and with helium shielding gas (10^{-5} G).

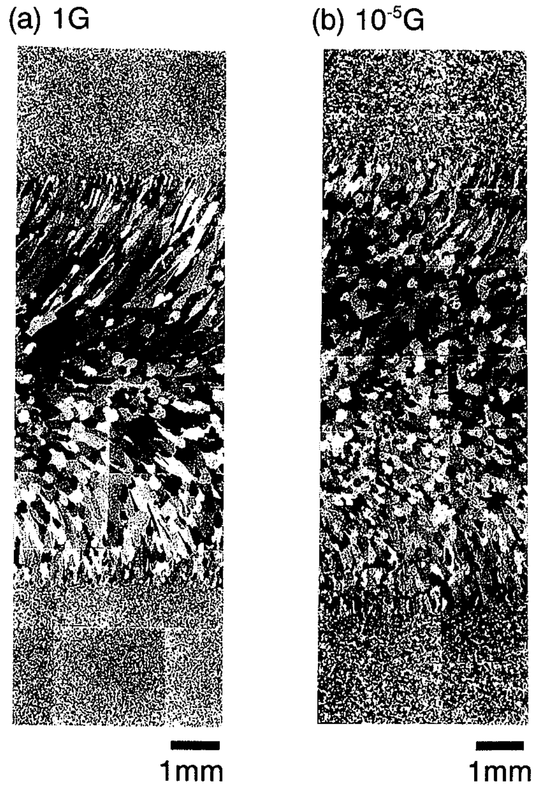


Fig. 11. Longitudinal sections of butt welds formed in horizontal welding with helium shielding gas in both environments.

Fig. 12. Feather crystal structures in butt welds of horizontal welding with helium shielding gas in terrestrial environment.

Figure 11 shows longitudinal sections of the butt welds formed in horizontal welding with helium shielding gas in both environments. The grain structures of the transverse sections in both environments look like the same structures, as shown in Figs. 4 and 5. However, when the longitudinal section is observed, it is found that the columnar grain structures are distributed throughout the butt weld with helium shielding gas in the terrestrial environment, and the equiaxed grain structures are distributed in the microgravity environment, as shown in Figs. 11(a) and 11(b). The weld pool size on the former condition was smaller, as seen in Fig. 5(a). Accordingly, the temperature gradient should have been larger.

In addition, only in the former condition, the feather crystal structure is observed in the middle part. **Figure 12** shows a magnified photograph of the feather crystal structure. The feather crystal structure is often formed in aluminum alloys when welding is performed at high heat input and at a low welding velocity.[13)] At a constant welding velocity, as the heat input increases, a grain structure formed varies from the columnar grain structure to the feather crystal structure and then to the equiaxed grain structure. Senda *et al.* reported that the feather crystal structure is formed in a temperature gradient between that for the columnar grain structure and that for the equiaxed grain structure.[13)] It is reasonable that the feather crystal structure was formed in the middle part of the weld.

(a) 1G

(b) 10^{-5}G

Fig. 13. Arc shape in vertical up welding with argon shielding gas.

4.5. Effect of Gravity on Arc Shape

Figure 13 shows the arc photographed using a welding filter (JIS 11) in both environments. In this study, the arc shapes are very similar in both environments, though Kaihara *et al.* reported that gravity affects the arc shape.[4] The difference in the results may be caused by the different transmissivity of the filters. When the transmissivity of a filter is lower, the image corresponds to a higher temperature region. When the transmissivity is higher, the image includes a lower temperature region. More detailed investigations are necessary on this point.

5. Conclusion

By performing welding both in a microgravity environment and in a terrestrial environment, the following points were found.

(1) The weld bead is formed flat in the microgravity environment and is significantly affected by gravity in the terrestrial environment.

(2) In the microgravity environment, a large amount of metal can be welded at once and in any welding position.

(3) When helium is used as a shielding gas, the weld bead formed is flatter than that formed using argon shielding gas because of the reduction of arc pressure.

(4) Judging from the distribution of the grain structures in the weld, in the microgravity environment, the temperature gradient is smaller than that in the terrestrial environment, and the degree of the constitutional supercooling is higher due to the absence of the heat transfer by gravity.

Acknowledgments

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